

Multi-Natural Inflation

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Abstract

We propose a multi-natural inflation model in which the single-field inflaton potential consists of two or more sinusoidal potentials that are comparable in size, but have different periodicity with a possible non-zero relative phase. The model is versatile enough to realize both large-field and small-field inflation. We show that, in a model with two sinusoidal potentials, the predicted values of the spectral index and tensor-to-scalar ratio lie within the 1σ region of the Planck data. In particular, there is no lower bound on the decay constants in contrast to the original natural inflation. We also show that, in a certain limit, multi-natural inflation can be approximated by a hilltop quartic inflation model.

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1 Introduction

The standard Λ CDM cosmology has been strongly confirmed by recent Planck observations [1]. In particular, the observed data is consistent with almost scale-invariant, adiabatic and Gaussian primordial density perturbations. This strongly suggests that our Universe experienced the inflationary expansion described by a simple (effectively) single-field inflation [2, 3].

Among many inflation models so far, there is an interesting class of models called large-field inflation in which sizeable tensor perturbations are generated. One of the large-field inflation models is chaotic inflation [4], and by now there are many concrete realizations of the chaotic inflation in supergravity [5, 6, 7, 8, 9, 10, 11] and superstring theory [12, 13] (see also e.g. Refs. [14, 15, 16, 17] for the development after the Planck results).

The tensor-to-scalar ratio r as well as the spectral index n_s are tightly constrained by the Planck data combined with other CMB observations as [1]

$$n_s = 0.9600 \pm 0.0071, \quad (1)$$

$$r < 0.11 \quad (95\% \text{CL}). \quad (2)$$

While n_s is determined by the shape of the inflaton potential, r is determined by the inflation energy scale, as long as the slow-roll inflation is assumed. Then the inflation scale is related to r as

$$H_{\text{inf}} \simeq 8.5 \times 10^{13} \text{ GeV} \left(\frac{r}{0.11} \right)^{\frac{1}{2}}, \quad (3)$$

where H_{inf} denotes the Hubble parameter during inflation, and the on-going and planned CMB observations will be able to probe $r \gtrsim 10^{-3}$.

In a single-field inflation model with a canonical kinetic term, there is a relation between r and the field excursion of the inflaton [18]. In particular, the inflaton field excursion exceeds the Planck scale if $r \gtrsim 0.01$, which places a strict requirement on inflation model building to have good control over inflaton field values greater than the Planck scale. One possibility is to impose an approximate shift symmetry on the inflaton so as to keep the inflaton potential sufficiently flat at super-Planckian values. The simplest realization is natural inflation [19, 20], in which the inflaton is a (pseudo) Nambu-Goldstone

(NG) boson, and its potential takes the following form,

$$V(\phi) = \Lambda^4 [1 - \cos(\phi/f)], \quad (4)$$

where the sinusoidal potential arises from some non-perturbative effects which explicitly break the shift symmetry. The predicted values of n_s and r are consistent with the Planck data for $f \gtrsim 5M_p$ [1], where $M_p \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck mass.

In this letter we consider an extension of natural inflation by adding another sinusoidal potential which modifies the inflaton dynamics at large field values, leading to different predictions of n_s and r .³ This is possible if there are multiple sources for the explicit breaking of the shift symmetry of the inflaton [21]. We shall give concrete examples later.⁴ Our model is versatile enough to realize both large-field and small-field inflation. We will show that the predicted values of n_s and r are consistent with the Planck data for a wide range of the decay constant. In particular, the sub-Planckian decay constant $f \ll M_p$ is allowed by the Planck data at 2σ ; the model is approximated by a hilltop quartic inflation model [3] in this limit.

Lastly let us briefly mention related works in the past. In the original natural inflation, the required decay constant $f \gtrsim 5M_p$ may be beyond the range of validity of an effective field theoretic description. One solution is to consider multiple axions (or NG bosons); in Ref. [24], it was pointed out that the effective large decay constant can be realized, leading to the (effectively) single-field natural inflation (4). See also Refs. [25, 26] for other ways to relax the bound. Using pseudo NG bosons, multi-field inflation models such as hybrid inflation were proposed in Refs. [27]. In string theory, there are racetrack inflation [28], N -flation [29], and axion monodromy [12, 13], in which the axions play the role of the inflaton; the first two models are multi-field inflation models, and the last one is equivalent to a linear-term chaotic inflation. Our model is a single-field inflation model based on multiple sinusoidal functions, and the inflaton potential as well as the predicted n_s and r are different from those of the natural inflation and the above models. Later we will briefly discuss a possible UV completion of our model.

³ Increasing the number of parameters is not favored from the Bayesian point of view.

⁴ Although our model is a simple toy model at this stage, the implementation in string-inspired supergravity [22] as well as its implications for a large running spectral index [23] were studied after the submission of this paper.

2 Multi-natural inflation

2.1 Natural inflation

Here let us summarize the results of natural inflation. Natural inflation arises from a broken global symmetry in order to generate a very flat potential necessary for inflation [19, 20]. The inflaton potential has the form

$$V(\phi) = \Lambda^4 [1 - \cos(\phi/f)]. \quad (5)$$

In a standard slow roll analysis there are two sufficient conditions for inflation, given by

$$\varepsilon(\phi) \equiv \frac{M_p^2}{2} \left(\frac{V_\phi}{V} \right)^2 \ll 1, \quad \eta(\phi) \equiv M_p^2 \left(\frac{V_{\phi\phi}}{V} \right) \ll 1, \quad (6)$$

where subscripts of ϕ denote derivatives with respect to the scalar field.

For natural inflation, the parameters ε and η become

$$\varepsilon(\phi) = \frac{1}{2} \left(\frac{M_p}{f} \right)^2 \left[\frac{\sin(\phi/f)}{1 - \cos(\phi/f)} \right]^2 \quad (7)$$

and

$$\eta(\phi) = \left(\frac{M_p}{f} \right)^2 \left[\frac{\cos(\phi/f)}{1 - \cos(\phi/f)} \right]. \quad (8)$$

To first order, the spectral index n_s and the tensor-to-scalar ratio r can then be calculated using (see e.g. Ref. [36]),

$$n_s = 1 - 6\varepsilon + 2\eta \quad (9)$$

and

$$r = 16\varepsilon. \quad (10)$$

The predicted (n_s, r) for natural inflation is consistent with the Planck data for $f \gtrsim 5M_p$ [1].

2.2 Multi-natural inflation

In multi-natural inflation we consider an inflaton potential that consists of two or more sinusoidal functions. As a minimal extension, let us consider a potential with two sinusoidal

terms. The potential takes the form⁵

$$V(\phi) = C - \Lambda_1^4 \cos(\phi/f_1) - \Lambda_2^4 \cos(\phi/f_2 + \theta), \quad (11)$$

where C is a constant that shifts the minimum of the potential to zero and θ is a non-zero relative phase. The last term shifts the potential minimum from the origin to $\phi = \phi_{\min}$, and also modifies the potential shape. This model is reduced to the original natural inflation in the limit of either $\Lambda_2 \rightarrow 0$ or $f_2 \rightarrow \infty$. As we shall see later, such two sinusoidal terms could be generated by two different non-perturbative sources. To simplify notation we set $f_1 = f$ and $\Lambda_1 = \Lambda$, and relate the parameters by,

$$f_2 = Af, \quad (12)$$

$$\Lambda_2^4 = B\Lambda^4, \quad (13)$$

where A and B are real and positive constants. Although in general Λ_2 , f_2 and θ are arbitrary parameters, we only investigate cases for which the second sinusoidal term gives relatively small perturbations, and the resulting potential is free of local minima so as to avoid the inflaton becoming trapped in a false vacuum. In general there are many other local minima and maxima at different values of ϕ . The stability of the vacuum at $\phi = \phi_{\min}$ is assumed in the following analysis.

We have solved the inflaton dynamics numerically. To be explicit, we have solved the inflaton equation of motion, $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$, with the inflaton potential given by (11), until the end of the accelerated expansion of the Universe. Then, we have identified the timing when the number of e-folds until the end of the inflation N is equal to 50 or 60, i.e., when the cosmological perturbations with the pivot scale, $k = 0.002 \text{ Mpc}^{-1}$, exited the horizon, and evaluated the slow-roll parameters at that time. We thus obtain the predicted values of (n_s, r) for a given inflaton potential. By repeating this procedure for different values of f , we obtain a line in the (n_s, r) -plane.

The resulting n_s and r predictions for varying values of Λ_2 and θ are shown in Figs. 1 and 2, respectively. Their corresponding potentials along with the positions on the potential for e-folding number $N = 60$ for various values of f/M_p are also shown.

⁵ The potential of this form with f_1/f_2 being an irrational number was considered in Ref. [37] in a context of solving the cosmological constant problem.

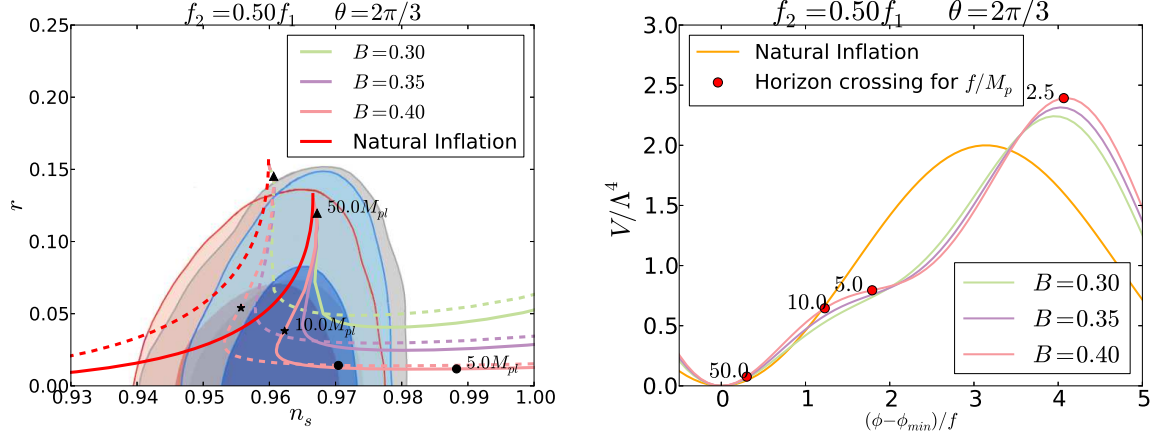


Figure 1: Left: the prediction of (n_s, r) of multi-natural inflation for three different values of Λ_2^4 . Solid (dashed) lines correspond to the e-folding number $N = 60$ ($N = 50$). Right: the corresponding inflaton potentials. The red dots represent the position at horizon crossing at $N = 60$ for the case of $B = 0.40$.

In Fig. 1, we set $A = 0.50$ and $\theta = 2\pi/3$, varying $B = 0.30, 0.35$ and 0.40 . From the left panel, we can see that the predicted (n_s, r) approach those of the original natural inflation as f increases. This is because, in the limit of large f , both models are reduced to the quadratic chaotic inflation. Interestingly, for moderately large f , the predicted curves come closer to the center values of the Planck results, compared to the natural inflation. We also note that, for $f \gtrsim 5M_p$, the behavior of (n_s, r) is similar to that of the polynomial chaotic inflation [15]. This is not surprising because, if one expands the inflaton potential around the potential minimum, multi-natural inflation can be approximated by the polynomial chaotic inflation for some choice of the model parameters. In the right panel, we see that, for smaller values of f , the perturbation crosses the horizon scale further up the potential and, consequently, where V_ϕ/V is relatively small. Since $r = 16\epsilon \propto (V_\phi/V)^2$, r decreases as f decreases. The behavior of n_s is more complicated since both the slope and curvature of the potential (through $\eta \propto V_{\phi\phi}/V$) play a role. As f becomes very large ($f \gtrsim 10M_p$), the potential at horizon crossing is close to the minimum and thus approaches the standard natural inflation solution. For $5M_p \lesssim f \lesssim 10M_p$, the ϵ -term in n_s (see Eq. (9)) becomes less important and n_s increases. As f decreases below $\sim 5M_p$, ϵ again begins to grow and thus so does r . Simultaneously, this causes

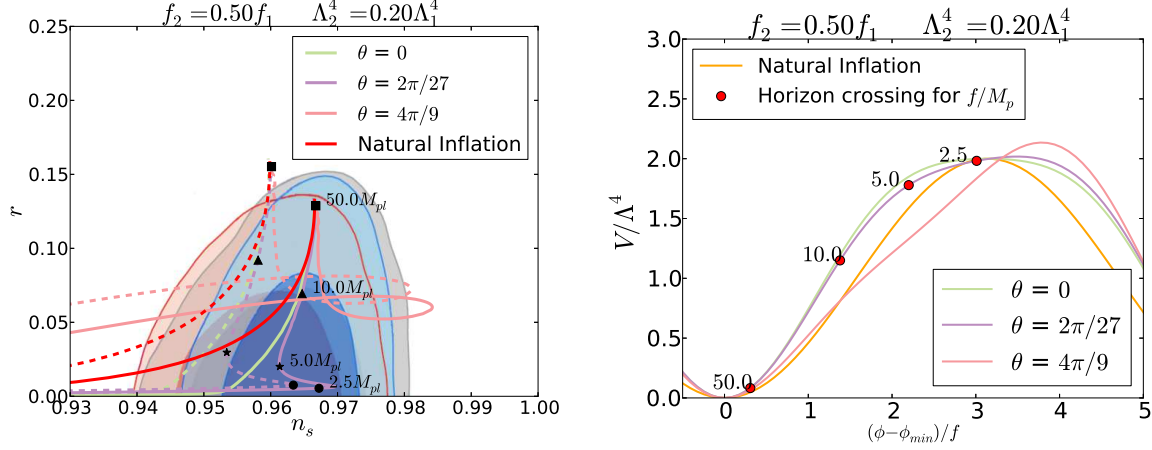


Figure 2: Same as Fig. 1 but for different values of the relative phase θ .

n_s to decrease as η becomes negative. This causes the (n_s, r) curve to loop back toward negative n_s , similar to the pink curve in Fig. 2. In this regime, however, the predicted (n_s, r) is well outside the allowed region and thus we neglect it in Fig. 1.

Next let us consider another case in which we set $A = 0.50$ and $B = 0.20$, varying the relative phase θ as $\theta = 0, 2\pi/27$, and $4\pi/9$. The behavior of n_s and r can be understood similarly. Compared to the previous case, there is a flat plateau around $\phi - \phi_{\min} \simeq \pi f$. This feature keeps the contribution of η to the spectral index small even for small values of f . As a result, the model is consistent with the Planck data for smaller values of f . In particular, the model agrees with Planck data in the 2σ region even for sub-Planckian values of f .

Our model (11) actually contains a hilltop quartic inflation model [1, 3] in a limiting case. The model is also referred to as new inflation. To see this, let us investigate potentials where the curvature vanishes at the top of the first sinusoidal term, $\phi/f = \pi$. The condition for vanishing curvature imposes the conditions

$$B = A^2, \quad \theta = -\frac{\pi}{A}. \quad (14)$$

Expanding (11) around $\phi/f = \pi$ our potential takes the form,

$$V = \Lambda^4 \left[1 - \frac{\tilde{\phi}^4}{\mu'^4} + \dots \right] \quad (15)$$

where we have defined $\tilde{\phi} \equiv \phi - \pi f$ and

$$\Lambda'^4 \equiv C + \Lambda^4(1 - A^2), \quad (16)$$

$$\frac{\Lambda'^4}{\mu'^4} \equiv \frac{(1 - A^2)\Lambda^4}{24A^2 f^4}. \quad (17)$$

For small $f \lesssim M_p$, cosmological scales exit the horizon while the inflaton sits near the top of the potential where the above expansion is valid. Interestingly, this approximation is similar to hilltop models of inflation, given by:

$$V \simeq \Lambda^4 \left[1 - \frac{\phi^p}{\mu^p} + \dots \right] \quad (18)$$

where $p = 4$ in our approximation. For $p = 4$, the spectral index n_s is given by,

$$n_s \simeq 1 - \frac{3}{N} \quad (19)$$

which for $N = 50$ ($N = 60$) is 0.94 (0.95). In Fig. 3 we show the behavior of n_s and r as a function of f for the parameters $A = 0.50$, $B = 0.25$ and $\theta = 0$. We see that, indeed, for the given parameter set and sub-Planckian values of f , multi-natural inflation approaches the hilltop quartic prediction. For $N = 60$, no lower bound on f is required by the Planck data. For $N = 50$, however, f is required to be larger than $5M_p$ as it predicts too small a value of n_s . As the e-folding number becomes smaller for smaller f , this tension at small values of f is real and requires some modification of the inflaton dynamics. In a context of new inflation in supergravity [30, 31], the resolution of the tension was discussed in detail, and it is known that the prediction of n_s can be increased to be consistent with the Planck data either by adding a logarithmic correction [32, 33] or a linear term [34], or by considering $p > 4$ [35]. In the multi-natural inflation, we can add another sinusoidal function so as to either give an effective linear term, or cancel both the curvature and the quartic coupling at the top of the potential.

We can constrain the height of the potential, $\Lambda^4 = \Lambda_1^4$, by imposing Planck normalization on the curvature perturbation [1]

$$P_{\mathcal{R}} \simeq e^{3.098} \times 10^{-10} \simeq 2.2 \times 10^{-9}. \quad (20)$$

Following Ref. [36], the scalar perturbation amplitude is given by

$$P_{\mathcal{R}}^{1/2} = \frac{H^2}{2\pi \left| \dot{\phi} \right|}, \quad (21)$$

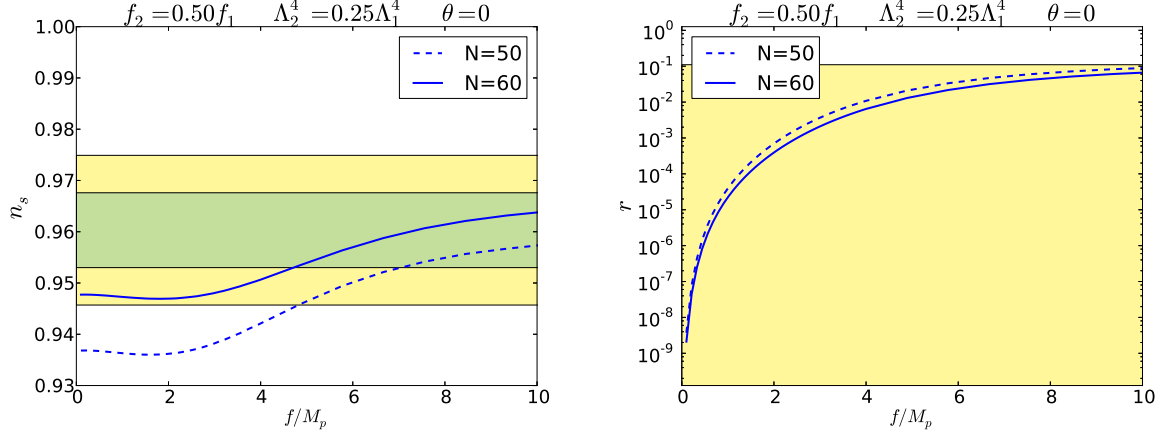


Figure 3: Behavior of n_s (left) and r (right) as a function of f . The shaded regions in the left figure correspond to 1 and 2σ allowed regions for n_s from Planck data. The shaded region on the right corresponds to the 95% CL for r ($r < 0.11$).

where the right-hand side is to be evaluated when the comoving wavelength of the perturbation crosses outside the horizon during inflation. Using the slow roll approximation, we find

$$P_{\mathcal{R}}^{1/2} \simeq \frac{3}{2\pi} \left(\frac{1}{3}\right)^{3/2} \frac{\Lambda^2 f [C - \cos(\phi/f) - B \cos(\phi/(Af) + \theta)]^{3/2}}{M_p^3 |\sin(\phi/f) + (B/A) \sin(\phi/(Af) + \theta)|}. \quad (22)$$

Fixing the parameters A, B and θ we can find Λ for varying f . As an example, Fig. 4 shows the behavior of Λ and the inflaton mass m_ϕ at the potential minimum for $0.5M_p \leq f \leq 15M_p$, again using the parameters $A = 0.50$, $B = 0.25$ and a zero relative phase. For large f we see that $\Lambda \sim 10^{16}$ GeV and $m_\phi \sim 10^{13}$ GeV.⁶

3 Discussion and Conclusions

We have extended natural inflation by adding another sinusoidal function. The origin of such shift-symmetry breaking terms could be due to non-perturbative effects. For instance, let us consider a complex scalar field Φ coupled to two sets of quark and anti-

⁶ We note that the inflaton mass at the potential minimum vanishes for $A^{-1} = 2i + 1$ with $i \in \mathbf{N}$. This can affect the reheating process of the inflaton.

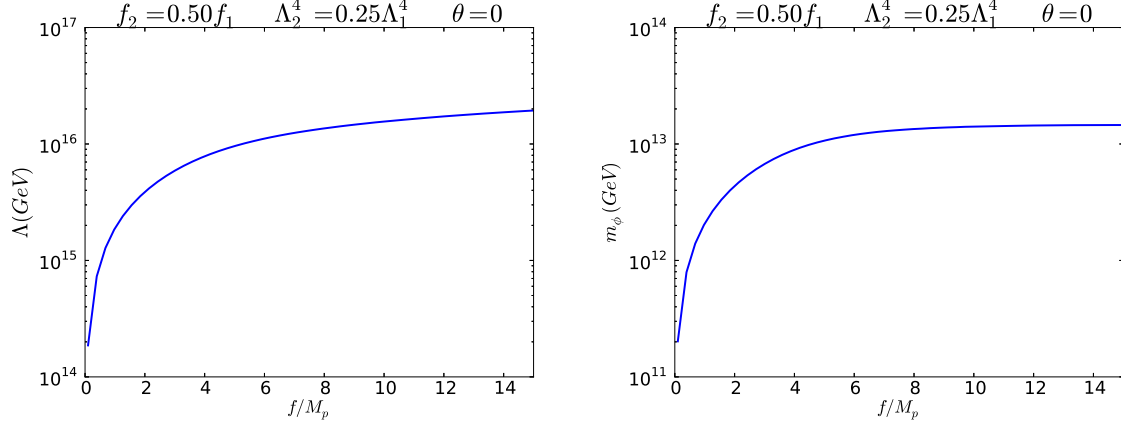


Figure 4: Planck normalized values for Λ (left) and m_ϕ (right) as a function of f .

quark fields,

$$\mathcal{L} = \sum_{i=1}^{n_q} y_i \Phi q_i \bar{q}_i + \sum_{j=1}^{n_Q} Y_j \Phi Q_j \bar{Q}_j, \quad (23)$$

where y_i and Y_j are coupling constants. Here q_i and \bar{q}_i are charged under a hidden non-Abelian gauge group G_1 , while Q_j and \bar{Q}_j under another non-Abelian group G_2 . To be concrete we take $G_1 = \text{SU}(N_1)$ and $G_2 = \text{SU}(N_2)$, and those (anti-)quarks are in the (anti)fundamental representation of each gauge group. Let us suppose that Φ respects a global $U(1)$ symmetry, $\Phi \rightarrow \Phi e^{i\alpha}$, which is explicitly broken by non-perturbative effects of the two gauge interactions. If Φ develops a non-zero vacuum expectation value (vev), its phase component becomes a Nambu-Goldstone boson, which we identify with the inflaton ϕ :

$$\Phi = \frac{v + \hat{s}}{\sqrt{2}} \exp \left[i \frac{\phi}{v} \right], \quad (24)$$

where v is the vev of Φ , and \hat{s} is the radial component. If \hat{s} is heavy enough, it can be integrated out. In the low energy limit, both G_1 and G_2 become strong, producing a potential for ϕ :

$$V(\phi) = \Lambda_1^4 \cos \left(\frac{\phi}{f_1} \right) + \Lambda_2^4 \cos \left(\frac{\phi}{f_2} + \theta \right), \quad (25)$$

where Λ_1 and Λ_2 denote the dynamical scale of G_1 and G_2 , respectively. The decay constants f_1 and f_2 are related to the vev of Φ as

$$f_1 = \frac{v}{n_q}, \quad f_2 = \frac{v}{n_Q}. \quad (26)$$

Thus, our model (11) corresponds to $A = n_q/n_Q$ and $B = \Lambda_2^4/\Lambda_1^4$. Note that A is a rational number in this case. In order to satisfy the Planck normalization, the dynamical scale should be of order 10^{15-16} GeV for $f_1 \sim f_2 \gtrsim \mathcal{O}(0.1)M_p$. Such a field theoretic description is considered to be valid for the decay constant f smaller than the Planck scale. As we have seen in the previous section, sub-Planckian values of f can fit the Planck data. Therefore, multi-natural inflation can be easily realized in an effective field theory.

It may be possible to embed multi-natural inflation into string theory, where an axionic component of moduli fields is identified with the inflaton, since there are various sources for the inflation potential such as gaugino condensations and instantons. This issue will be discussed in details elsewhere [22].

We have so far focused on the case of two sinusoidal functions (11). It is straightforward to consider multiple sinusoidal functions. In order to have successful inflation for the decay constants of order the Planck scale or below, we need to arrange those sinusoidal functions so that they conspire to make the inflaton potential sufficiently flat. As one of the slow-roll parameter η is of order unity in the original natural inflation with $f \sim M_p$, this requires a typical fine-tuning of $\mathcal{O}(1)\%$. As we have seen in the previous section, considering more than two sinusoidal functions, we can increase the prediction of n_s to be consistent with the Planck data for small values of f .

The inflaton needs to have couplings with the standard model particles for successful reheating. We may introduce dilatonic couplings,

$$\mathcal{L} = c \frac{\phi}{f} F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad (27)$$

where c is a coupling constant, and $F_{\mu\nu}$ denotes the field strength of the standard-model gauge fields. Such interactions can be induced if the heavy quarks q or Q in Eq. (23) are also charged under the standard-model gauge symmetry. For $f \sim M_p$ and $m_\phi \sim 10^{13}$ GeV,

the resultant reheating temperature is expected to be of order 10^{8-10} GeV, depending on the size of c . The thermal leptogenesis [38] is possible for such high reheating temperature.

In this letter we have studied a multi-natural inflation model where the single-field inflaton potential is given by a sum of two or more sinusoidal potentials comparable in size but with a slightly different periodicity as well as a possible non-zero relative phase. The model is versatile enough to realize both large-field and small-field inflation. We have shown that, in a model with two sinusoidal terms, the predicted values of the spectral index and the tensor-to-scalar ratio are consistent with the Planck data; they come closer to the center values of the Planck results, compared to natural inflation. The on-going and planned B-mode polarization experiments will be able to probe a large portion of the parameter space of our model. We have also shown that our model can be approximated by the hilltop quartic model in a limiting case. In particular, the spectral index lies within the 2σ allowed region even for decay constants much smaller than the Planck scale. Therefore there is no lower bound on the decay constants. This result should be contrasted to the original natural inflation, which is consistent with the Planck data only for decay constants greater than $\sim 5M_p$. This eases the difficulty of implementing the multi-natural inflation in an effective field theory.

Note added: After the submission of our letter, the BICEP2 experiment found the primordial B-mode polarization [39]. Although it needs to be confirmed by other experiments, this discovery makes it plausible that our model can be supported or refuted by future observations.

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